

Heliogyro Solar Sail Structural Dynamics, Control and Experimentation

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Heliogyro Description



Proposed by Richard MacNeal in 1968. NASA considered it for a Comet Halley rendezvous mission in the 1970s. Some additional design work done at Carnegie Melon during the 1990s and MIT in the 2000s.

CONCEPT:

- Several extremely long blades spun about a central hub

SAIL STIFFENING:

- Centrifugal

STOWAGE/DEPLOYMENT:

- Stored on spools
- Deployed with centrifugal force

ATTITUDE CONTROL:

- Via cyclic and collective blade pitch maneuvers
- Similar to a helicopter





Heliogyro Maneuvers

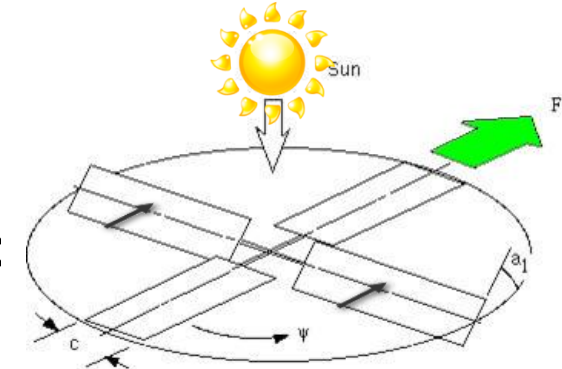
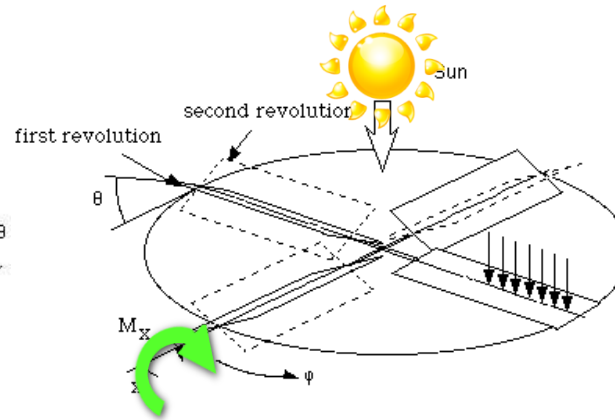
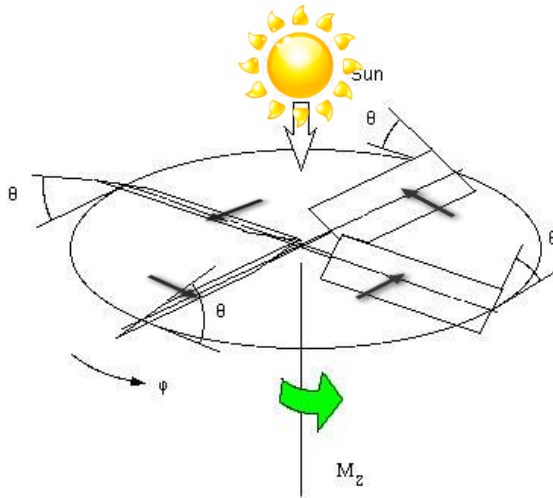


Collective

$\frac{1}{2}$ -Period Cyclic

1-Period Cyclic

Maneuver



Effect

Torque about spin (z) axis

Spin axis precession torque

Generate in-plane thrust

Purpose

Increase angular momentum during sail deployment

Attitude control

Change thrust direction (faster than slewing entire S/C)

[MacNeal 1967, 1978]



Heliogyros: PROS and CONS

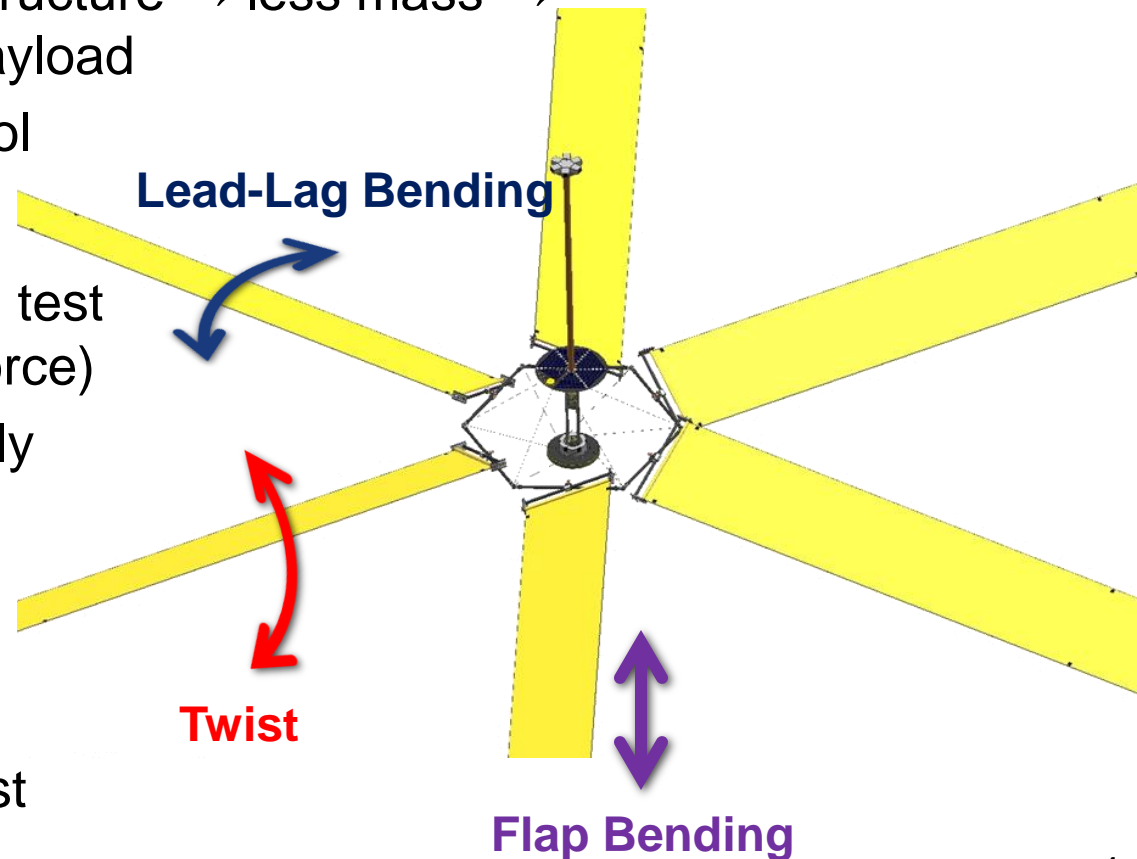


PROS:

- Spools make blades easy to stow and deploy
- Easier to scale to large sizes than square or disk sails
- Eliminates non-propulsive structure → less mass → higher acceleration/larger payload
- Propellantless attitude control

CONS:

- Difficult to accurately ground test (gravity $\sim 70\times$ > centrifugal force)
- Blade dynamic stability poorly understood
- Controlling blade twist is particularly difficult
- Expect very little material damping and stiffness in twist

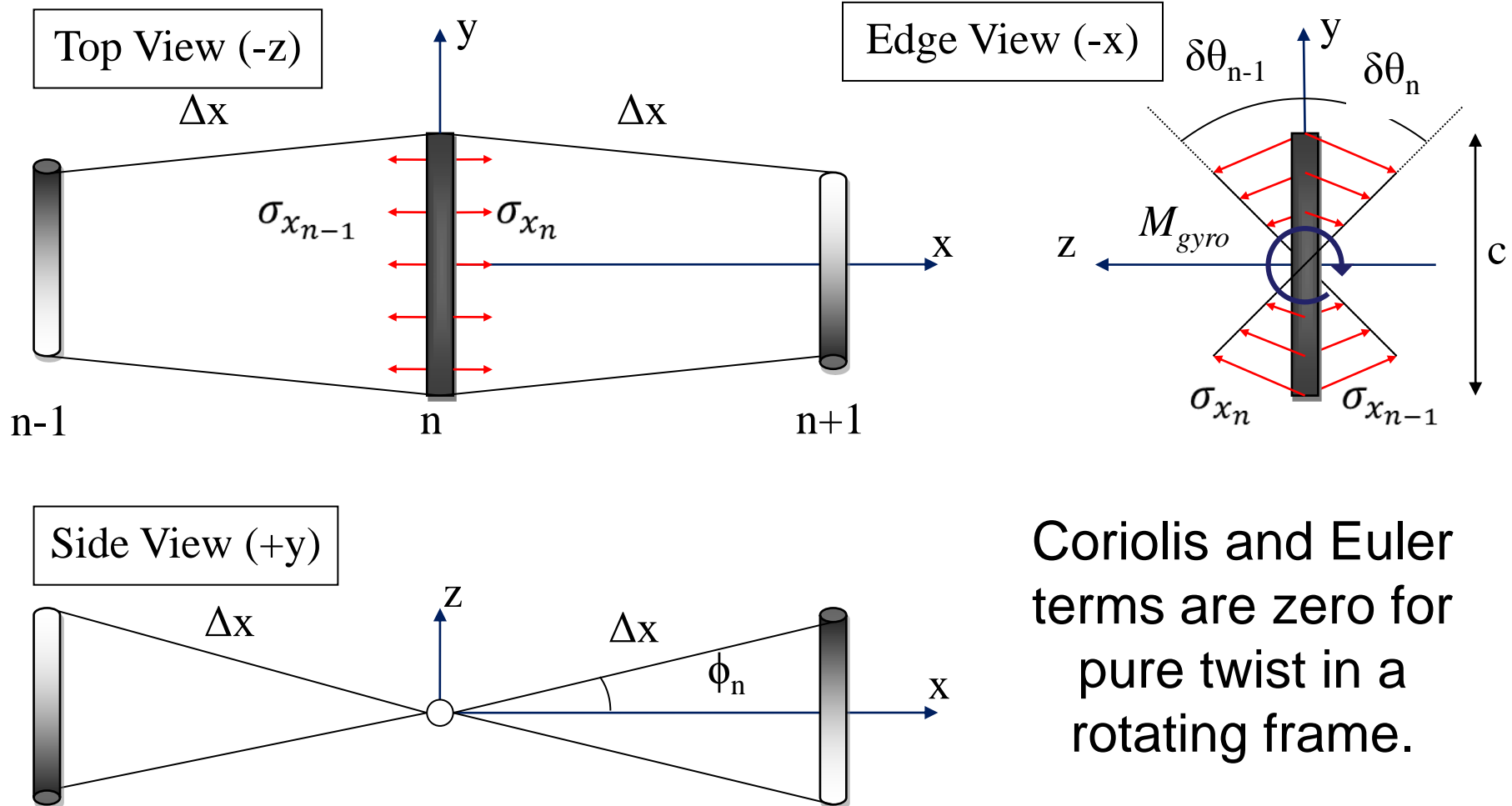




The Membrane Ladder: Uncoupled Twist Finite Element Method



$$\sum M_x = J_n \ddot{\theta}_n = -J_n \Omega^2 \theta_n + \frac{\sigma_{x_n} I_n}{\Delta x} (\theta_{n+1} - \theta_n) - \frac{\sigma_{x_{n-1}} I_{n-1}}{\Delta x} (\theta_n - \theta_{n-1}) + d \frac{1}{\Delta x} (\dot{\theta}_{n+1} - 2\dot{\theta}_n + \dot{\theta}_{n-1})$$



Coriolis and Euler terms are zero for pure twist in a rotating frame.



The Membrane Ladder's Assumptions: Uncoupled Twist Finite Element Method



$$J_n \ddot{\theta}_n = -K_{gyro_n} \theta_n + K_{cent_n} (\theta_{n+1} - \theta_n) - K_{cent_{n-1}} (\theta_n - \theta_{n-1}) + d \frac{1}{\Delta x} (\dot{\theta}_{n+1} - 2\dot{\theta}_n + \dot{\theta}_{n-1}) + M_{ext_n}$$

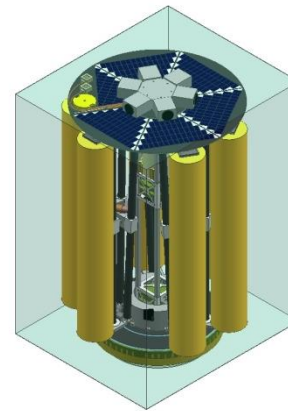
- No blade cambering
- No elastic torsional stiffness (only centrifugal stiffening)
- Linear material damping (stand-in for unknown damping)
- Linearize by small angle approximations. Reasonable because:
 - Gyroscopic stiffness (K_{gyro_n}) is 100 to 1000 times smaller than the centrifugal stiffness (K_{cent_n}).
 - K_{cent_n} depends on the difference in pitch ($\theta_{n+1} - \theta_n$).
 - $(\theta_{n+1} - \theta_n)$ is small.



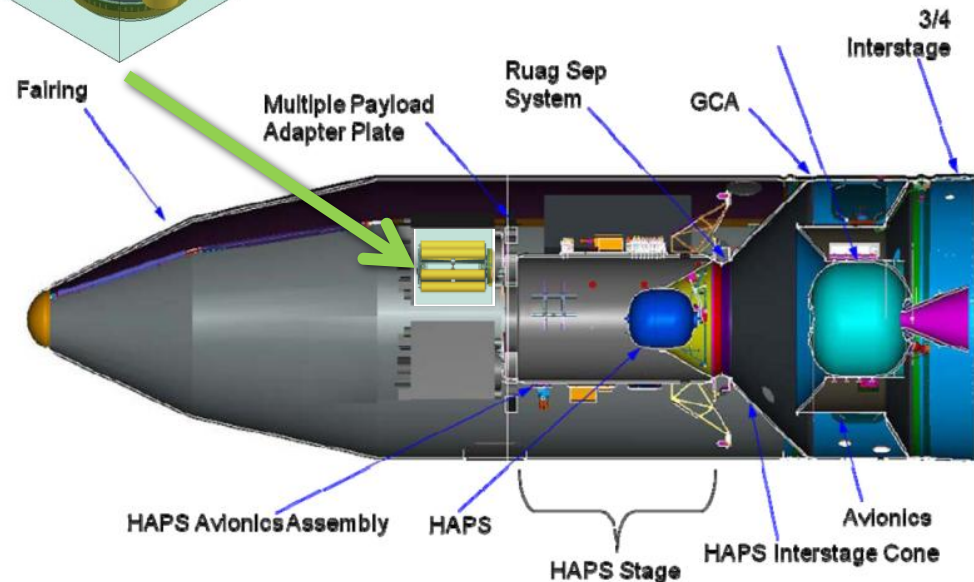
High-performance, Enabling, Low-Cost, Innovative, Operational Solar Sail (HELIOS)



Sail material	Al/Mylar
Sail Thickness	2.54 μm
# of blades	6
Blade chord	0.765 m
Blade radius	250 m
Sail area	1148 m^2
Sail system mass	14.6 kg
Bus mass	4.9 kg
Total mass	19.5 kg
Sail reflectivity	0.85
Characteristic acceleration	0.5 mm/s^2
Spin period	3 min
Orbit	LEO/GTO



HELIOS sail-craft with ESPA envelope



*Characteristic acceleration is defined using solar radiation pressure at 1AU with the heliogyro's rotational plane normal to the sun.

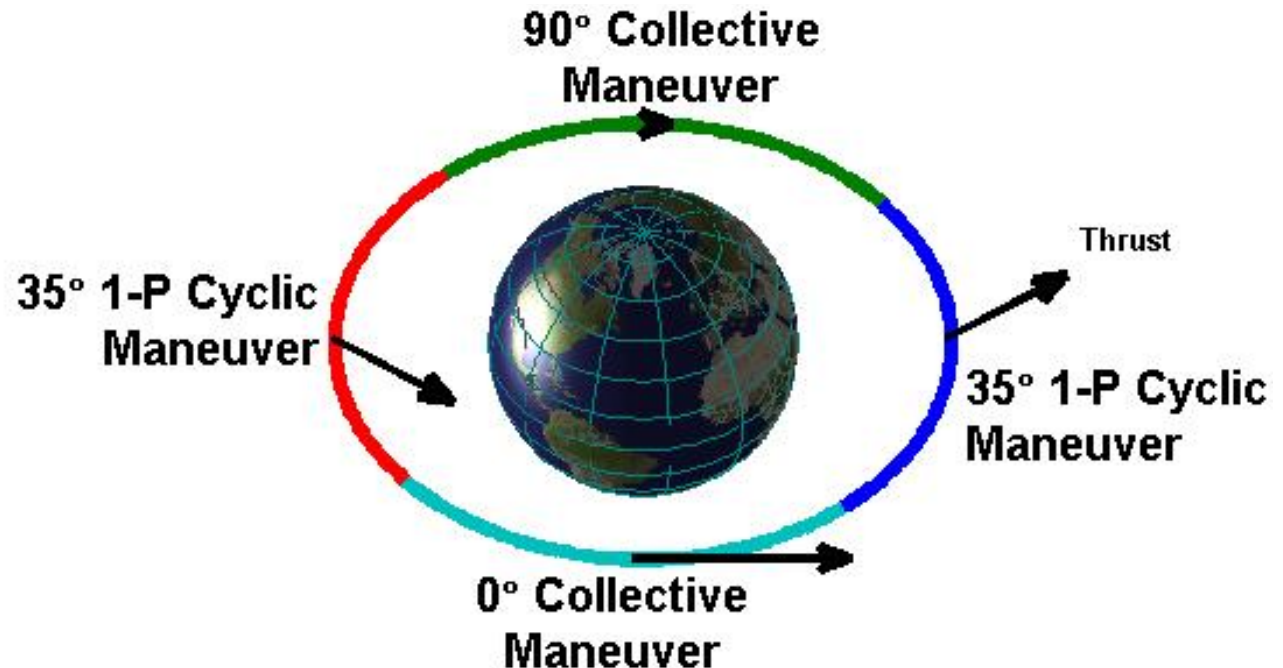
- 0.007 mm/s^2 for IKAROS, the only solar sail ever flown [Funase 2011]
- 0.07 mm/s^2 for Dawn's ion drive [dawn.jpl.nasa.gov].



Settling Time Requirement



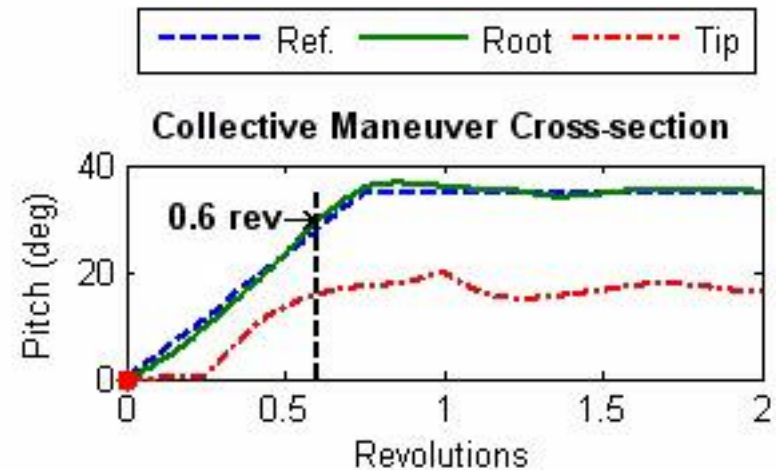
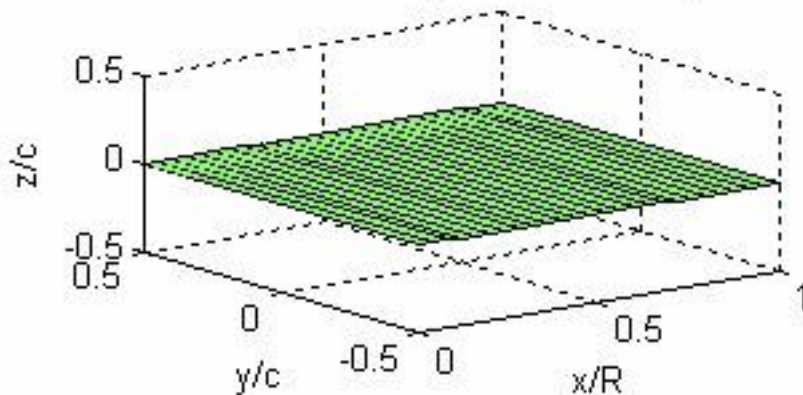
- One equatorial orbit raising scheme [MacNeal 1967] requires 4 maneuvers per orbit.
- We use a settling time goal of $1/8^{\text{th}}$ of an orbit or 4 revs (12 min) for the HELIOS mission in a 1000-1400 km LEO.
- The most challenging environment for solar sails is equatorial LEO, but...
- There are more ride-share opportunities at this orbit.



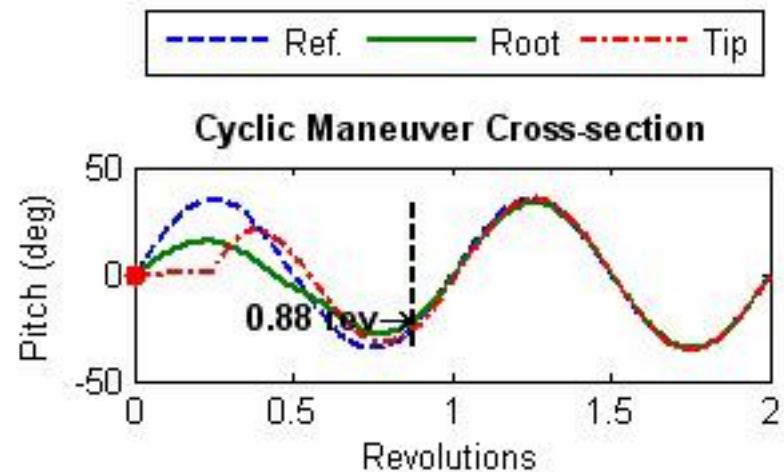
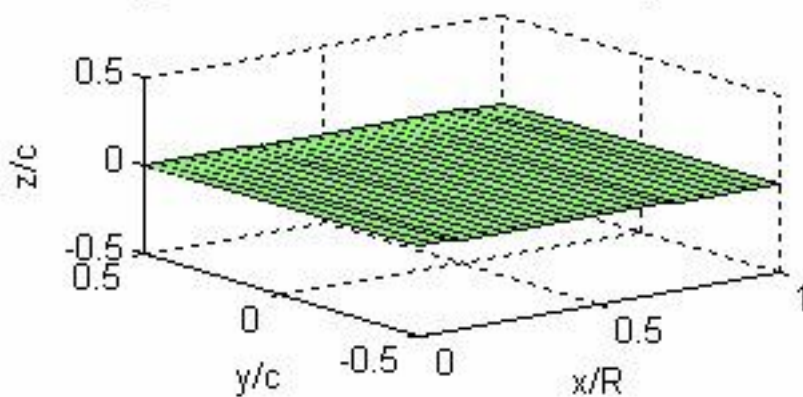


All maneuvers settle well within HELIOS mission requirement of 4 revolutions

Collective Maneuver, 20x time compression

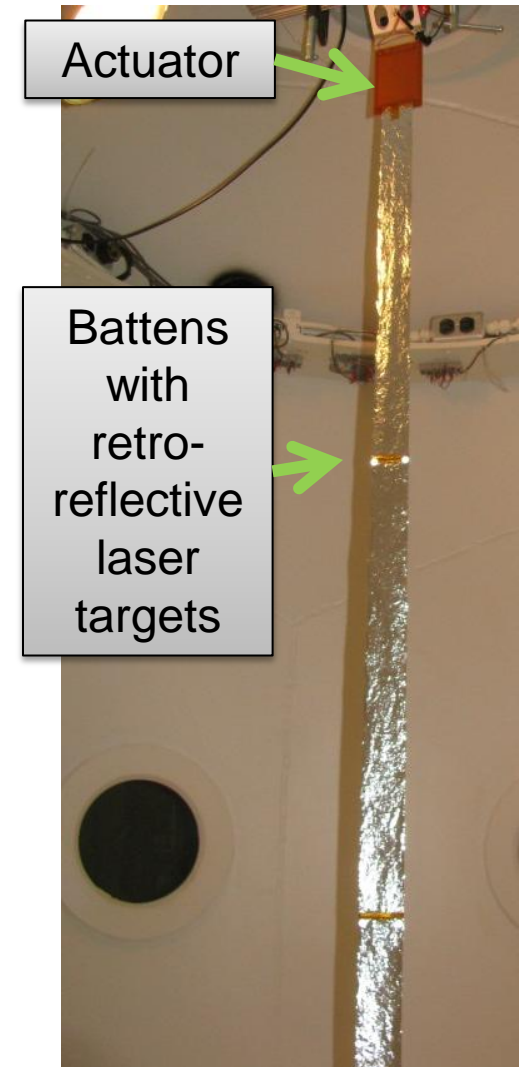
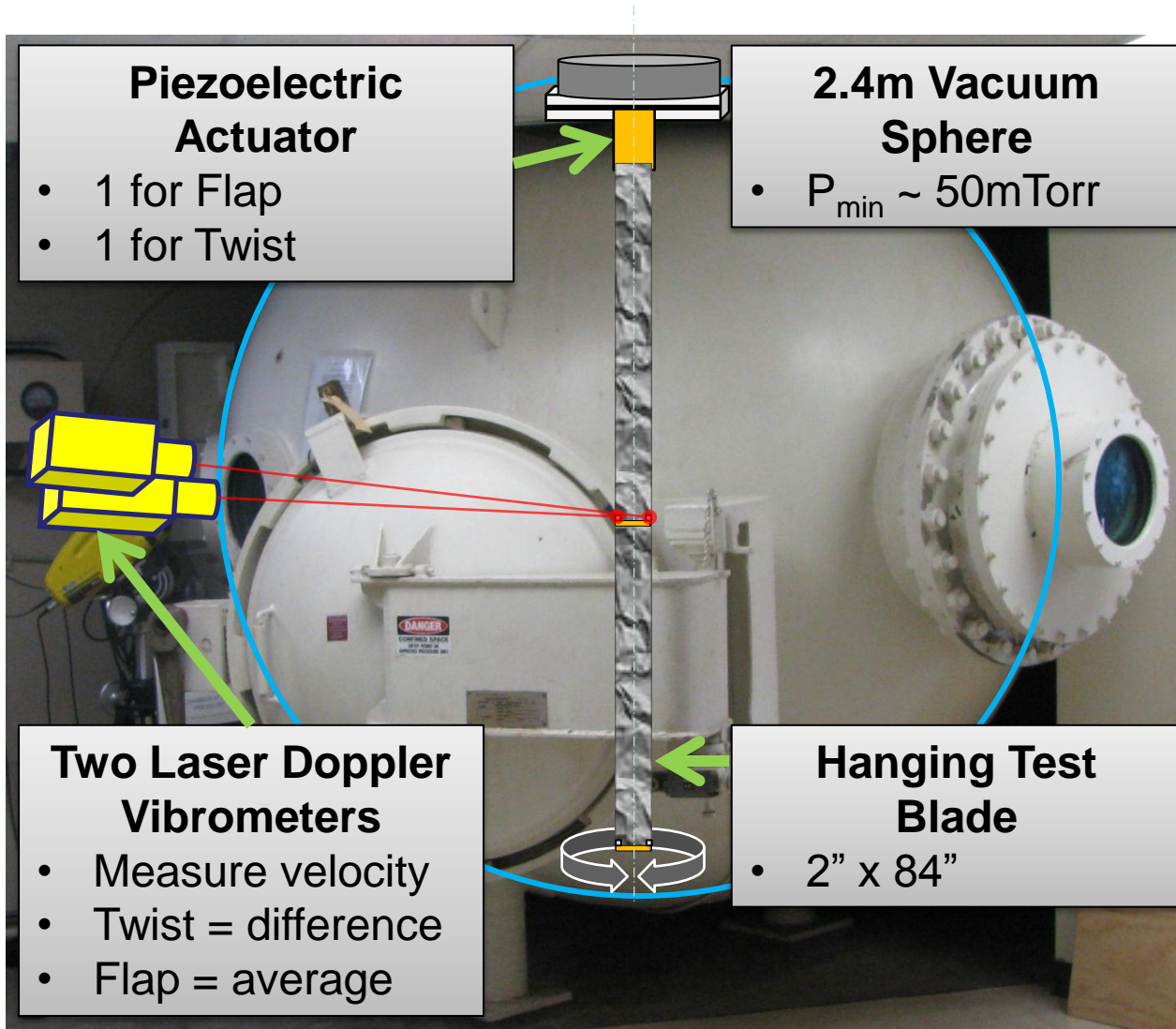


Cyclic Maneuver, 20x time compression





Hanging-blade Experimental Setup





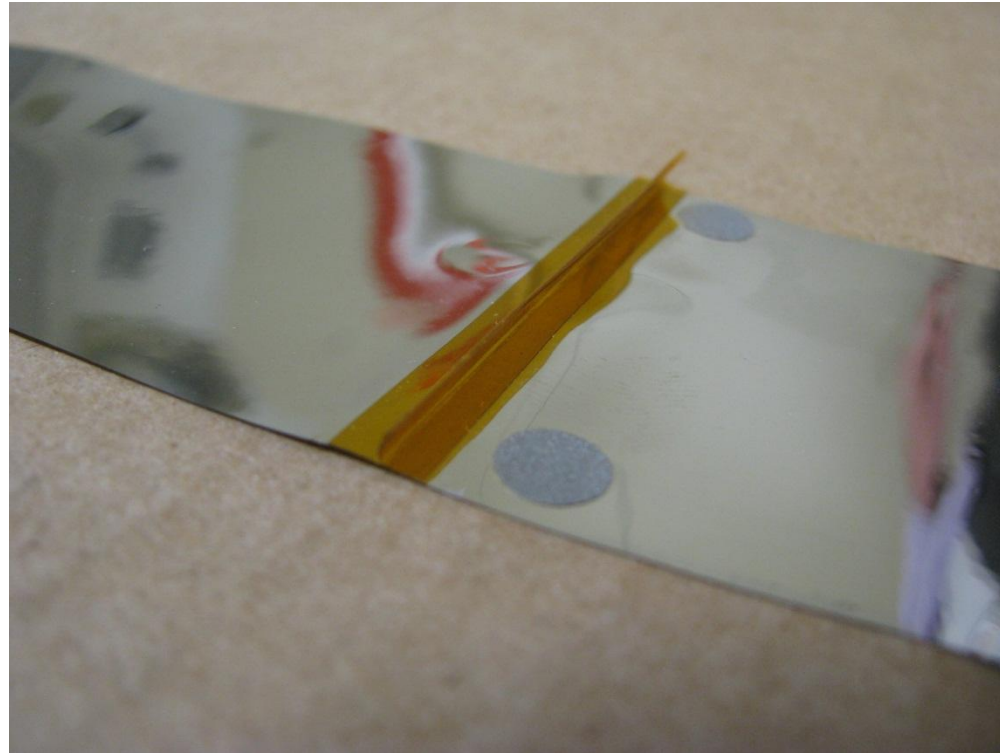
Goals

- Validate the membrane-ladder finite element model
- Estimate the material damping
- Qualitatively explore blade construction factors with several test articles:

Test Article	Material	Width (in)	Crumpled	Edge Reinforcing
1	1 mil Kapton	2	no	no
2	0.1 mil Mylar	2	no	no
3	0.1 mil Mylar	2	yes	no
4	0.1 mil Mylar	2	no	yes
5	0.1 mil Mylar	2	yes	yes



#1: 2", 1mil, Al Kapton, 4 Tape Battens



Sail:

- 3.85g

4 Battens:

- 0.24g
- 6% increase in total sail mass

Total:

- 4.10g

Fairly flat, but too thick and heavy





#2: 2", 0.1mil, Al Mylar, 4 Tape Battens



Sail:

- 0.39g

4 Battens:

- 0.30g
- 79% increase in total sail mass

Total:

- 0.70g

Unacceptable blade cambering/curl due to residual stress

→ Not tested





#3: 2", 0.1mil, Al Mylar, hand-crumpled



Sail:

- 0.39g

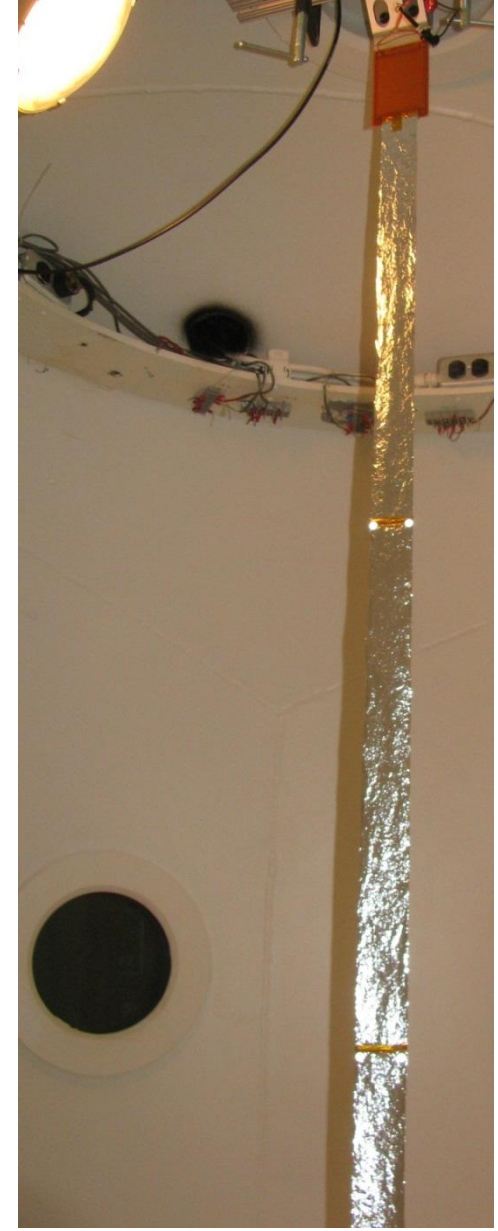
4 Battens:

- 0.30g
- 79% increase in total sail mass

Total:

- 0.70g

**Crumpling randomizes the residual stress
→ improved flatness**





#4: 2", 0.1mil, Al Mylar, Edge Reinforcing



Sail:

- 0.39g

4 Battens:

- 0.30g
- 79% increase in total sail mass

Edge Reinforcing:

- 1.45g
- 375% increase in total sail mass

Total:

- 2.13g

**Still a lot of cambering between
battens**

Huge mass penalty





#5: 2", 0.1mil, Al Mylar, Edge Reinforcing, Crumpled



Sail:

- 0.39g

4 Battens:

- 0.30g
- 79% increase in total sail mass

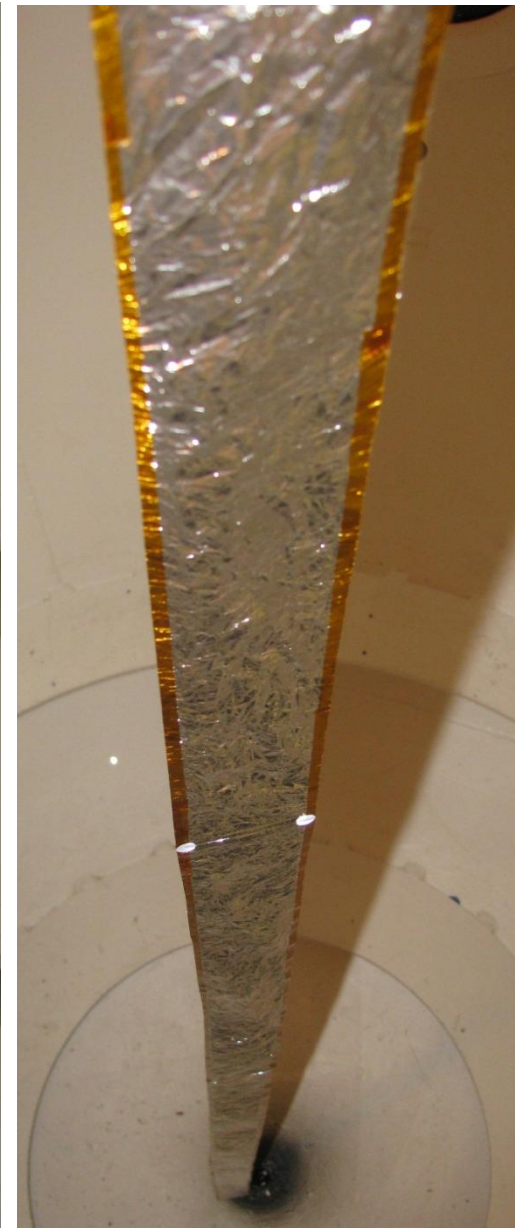
Edge Reinforcing:

- 1.45g
- 375% increase in total sail mass

Total:

- 2.13g

Flattest specimen
Significant mass penalty



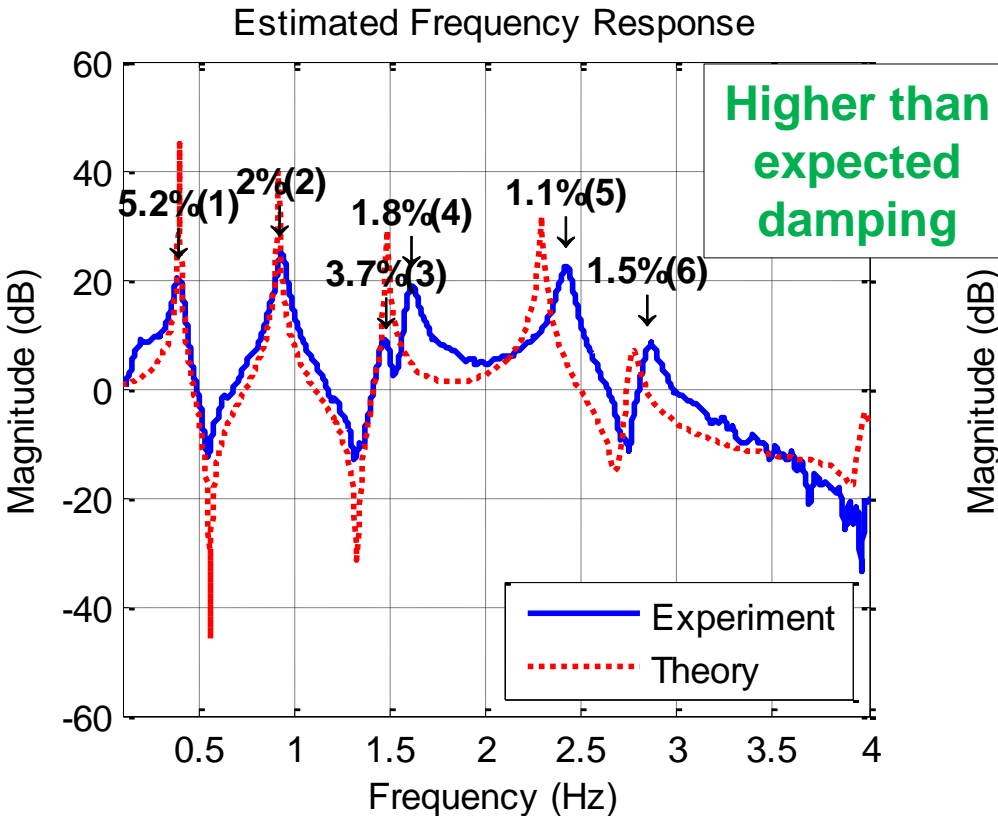


Experimental and theoretical FRFs at the blade midpoint, Article #3 (crumpled)

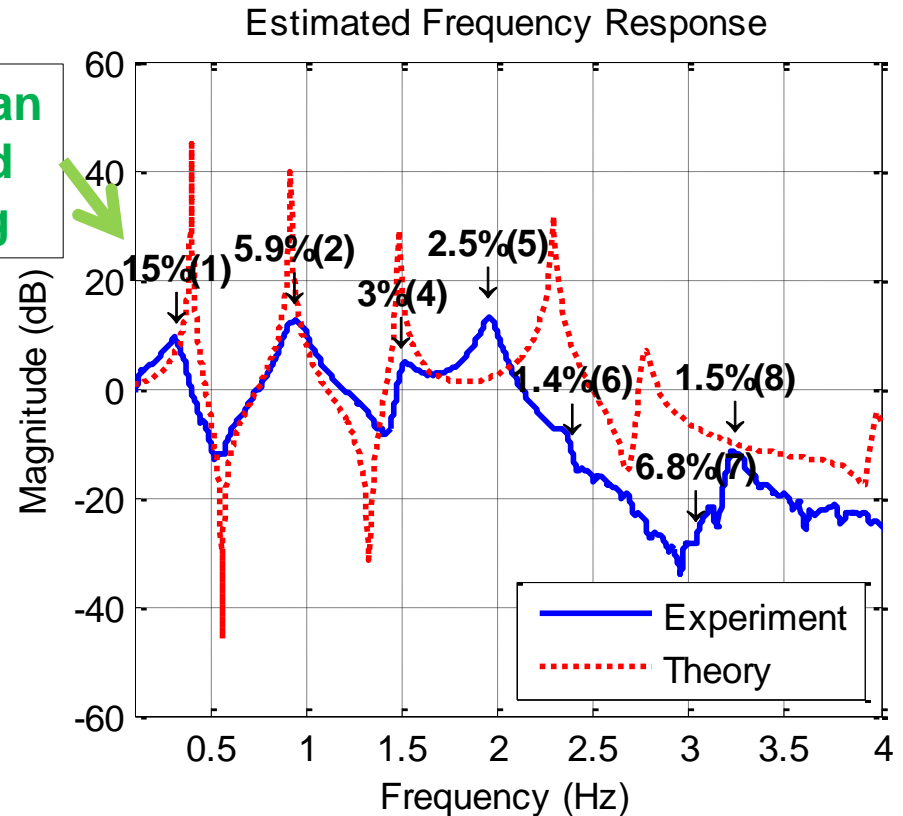


Flap response with flap actuator

Twist response with twist actuator



5.5% RMS difference in modal frequency from theory (first 5 modes)



11.5% RMS difference in modal frequency from theory (first 4 modes)



Summary



#	Material	Crump.	Edge Reinf.	Mass (g)	Agreement with Theory		1 st Mode Damping	
					Flap	Twist	Flap	Twist
1	1mil Kapton	no	no	4.10	N/A	80%	N/A	3.3%
2	0.1mil Mylar	no	no	0.70	N/A	N/A	N/A	N/A
3	0.1mil Mylar	yes	no	0.70	95%	89%	5.2%	17.5%
4	0.1mil Mylar	no	yes	2.13	92%	76%	4.4%	5.0%
5	0.1mil Mylar	yes	yes	2.13	96%	88%	3.5%	6.1%



Conclusions



- The HELIOS design can achieve mission-enabling accelerations and is a good stepping-stone for future heliogyro missions.
- Blade pitch control is not as difficult as originally assumed.
 - A blade pitch motor at the root with a PDFF controller is effective at controlling blade twist.
 - Experimental results agreed surprisingly well with the FEM theory.
 - Damping is higher than expected.
- Blade construction is a significant challenge.
 - Residual stresses cause significant curling in ultra-thin membranes.
 - Crumpling is an easy, mass-efficient way to improve flatness, but it lowers optical efficiency.



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Questions?

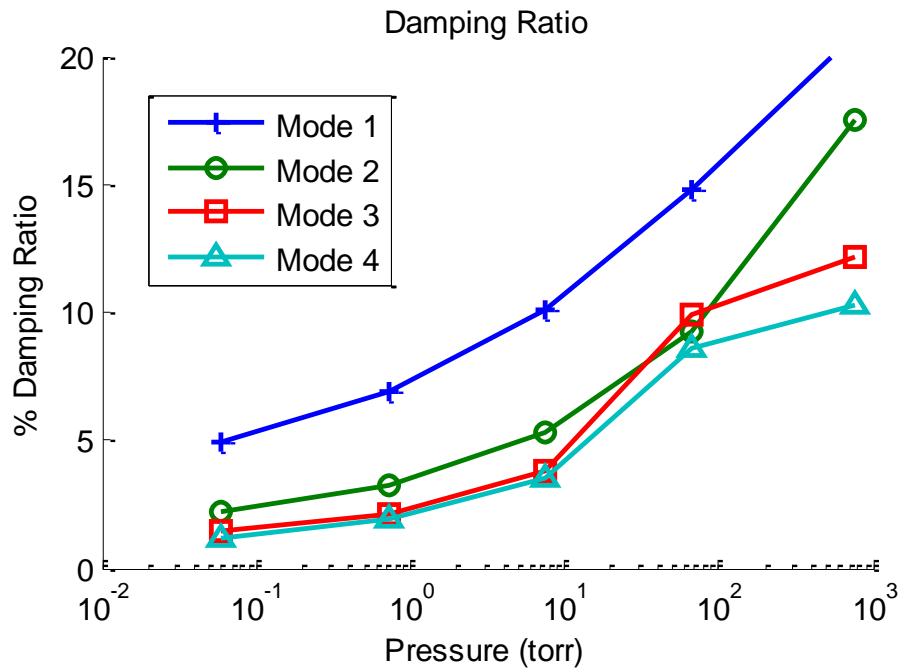




Variation of Damping with Pressure



Flap Response, Flap Actuator



Twist Response, Twist Actuator

